

Dynamical and radiative properties of astrophysical supersonic jets

I. Cocoon morphologies

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Abstract. We present the results of a numerical analysis of the propagation and interaction of a supersonic jet with the external medium. We discuss the motion of the head of the jet into the ambient in different physical conditions, carrying out calculations with different Mach numbers and density ratios of the jet to the exteriors. Performing the calculation in a reference frame in motion with the jet head, we can follow in detail its long term dynamics. This numerical scheme allows us also to study the morphology of the cocoon for different physical parameters. We find that the propagation velocity of the jet head into the ambient medium strongly influences the morphology of the cocoon, and this result can be relevant in connection to the origin and structure of lobes in extragalactic radiosources.

1. Introduction

Since the pioneering work by Norman et al. (1982), many numerical studies have been devoted to the analysis of the propagation of a supersonic jet shot into an ambient medium. The first studies (Norman et al. 1982, 1983, 1984; Wilson & Scheuer 1983) showed the main features of the interaction between jet and environment. We can describe the basic picture which emerged from those results in the following way: the deceleration of the jet flow at its head is accomplished through the formation of a strong shock (Mach disk) which thermalizes the jet bulk kinetic energy; the overpressured shocked jet material forms a backflow along the sides of the jet and inflates a cocoon whose size increases decreasing the density ratio between jet and ambient material; finally, a second shock (bow shock) is driven into the external medium. This basic picture bore also a suggestive resemblance with the structures seen in radio maps of extragalactic jets and brought to the association of the compact hot spots with the working surfaces where the jet dissipates its kinetic energy and of the radio lobes with the cocoons formed by the jet waste material. The following studies introduced many different ingredient to the basic model in order to make it more similar to the real astrophysical situation (for a recent review

see e.g. Burns, Norman & Clarke 1991). These ingredients include variability of the injection properties of the jet (Clarke & Burns 1991), variation of the physical parameters of the ambient medium along the jet propagation path (Norman, Burns & Sulkanen 1988) and nonadiabaticity of the flow, relevant to the case of stellar jets (Blondin, Fryxell & Königl 1990). There have been also attempts to study the fully 3-D case (Norman, Stone & Clarke 1991, Hardee & Clarke 1992, Hardee, Clarke & Howell 1995) and to introduce MHD effects (Clarke, Norman & Burns 1986; Lind et al. 1989). More recently, numerical simulations of relativistic jets have been carried out by Martí, Müller & Ibáñez (1994) and Duncan & Hughes (1994), for low Mach number jets, and by Martí et al. (1995) for high Mach number jets.

In spite of these strong efforts many aspects of this problem are still not well understood. This is due to the complexity of the jet-cocoon structure: in fact, the cocoon excites perturbations to the jet flow, which in turn can be amplified by the Kelvin–Helmholtz mechanism and induce a strong activity of the jet’s head that affects the cocoon structure. Thus a complex feedback loop mechanism establishes between jet and cocoon which make the dynamics of the interaction very complex. In addition, when trying a more direct comparison of the results with observations, one must remember that what is observed is an outcome of the distribution of energetic particles and magnetic field and not the bulk of the flowing plasma, and therefore direct comparisons could be misleading. In this paper and in a companion one (Massaglia et al. 1995, henceforth Paper II) we try to elucidate some of these aspects. Here we focus on the dynamics of the interaction and we describe some properties of the cocoon structure which can be relevant for the observational properties of extragalactic radio–sources and have been overlooked in previous studies. We have been able to examine these properties because of the wide exploration of the parameter space especially towards high Mach numbers, typically higher than those discussed in the present literature (see however Loken et al. 1992 for one simulation with Mach number in the range considered here), and because our approach allowed us to follow the jet propagation up to very long times and to keep all parts of the cocoon in the computational domain, whereas the usual approach is limited to follow the jet only for one crossing time of the grid and to lose the back part of the cocoon. In the companion Paper II, we focus instead on the radiative properties following the distribution of a passive magnetic field and of relativistic particles subject to synchrotron losses and to adiabatic expansion.

The outline of the paper is the following. In the next Sec. II we discuss the physical problem; the numerical scheme is examined in Sec. III; the results of the simulations of the jet’s head are reported in Sec. IV; the application of the results to astrophysical jets in radio sources are discussed in Sec. V.

2. The Physical Problem

We study the dynamics of a supersonic, cylindrical, axisymmetric jet continuously

injected in a medium initially at rest. We solve numerically the full set of adiabatic, inviscid fluid equations for mass, momentum, and energy conservation,

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) &= 0, \\ \rho \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} &= -\nabla p, \\ \frac{\partial p}{\partial t} + (\vec{v} \cdot \nabla) p - \Gamma \frac{p}{\rho} \left[\frac{\partial \rho}{\partial t} + (\vec{v} \cdot \nabla) \rho \right] &= 0\end{aligned}$$

where the fluid variables p , ρ and \vec{v} are, as customary, the pressure, density, and velocity, respectively; Γ is the ratio of the specific heats.

In order to follow the jet particles in the external environment, we solve an additional advection equation for a scalar field f :

$$\frac{\partial f}{\partial t} + (\vec{v} \cdot \nabla) f = 0.$$

The initial spatial distribution for this tracer is designed to demarcate the jet alone; thus, we set f initially equal to one inside the jet, and to zero outside; in the following evolution, f is set to one also for the newly injected jet fluid. By this means, we can distinguish between the matter which is initially part of the jet or is afterwards injected in the jet, and that which is part of the external medium.

Similar calculations found in the literature (see, e.g., Norman et al. 1982, 1984; Lind et al. 1989) are done injecting the jet from the left boundary in a medium at rest. In this way i) one is limited to follow the evolution of the jet's head only up to the time when it reaches the right boundary of the computational grid, and ii) it is not possible to determine the geometrical structure resulting from the interaction of the jet with the ambient medium since the back part of this structure is lost out of the left boundary of the domain. Since our main goal is to follow the long term evolution of this structure, we have overcome this difficulty by carrying out the actual computations in a reference frame in which the jet's head is nearly at rest and well inside the computational domain (see Fig. 1). Therefore, in the initial configuration, the external medium moves at a uniform velocity $-V_h$, where

$$V_h = \frac{v_j}{1 + \sqrt{\nu}},$$

where v_j is the jet velocity in the ‘laboratory frame’ and ν is the ratio of the external to the jet density, and V_h is an approximated advance velocity of the jet's head (see below §4.2). This moving frame is adopted in the computations, but afterwards, we will discuss the results obtained, translating them back in the reference frame where the external medium is at rest, i.e. in the ‘laboratory frame’.

Thus, the jet initially occupies a cylinder of length L (see Fig. 1), in pressure equilibrium with the external medium and the initial flow structure has the following

form:

$$v_z(r) = \begin{cases} \frac{v_z(r=0)}{\cosh[(r)^m]} - V_h & , \quad z \leq L , \\ -V_h & , \quad z > L . \end{cases} ,$$

where m is a ‘steepness’ parameter for the shear layer separating the jet from the external medium. The choice of separating the jet’s interior from the ambient medium with a smooth transition, instead of a sharp discontinuity, avoids numerical instabilities that can develop at the interface between the jet’s proper and the exteriors, especially at high Mach numbers.

The density radial dependence has the form:

$$\frac{\rho(r)}{\rho(r=0)} = \nu - \frac{\nu - 1}{\cosh[(wr)^n]} .$$

We have carried out a series of calculations setting $w = 0.75$, $m = 8$ and $n = 2m$; this implies a narrower and smoother radial extension of the ‘density’ jet with respect to the ‘velocity’ jet. The reason for this choice is to obtain a smooth radial profile of the momentum density ρv_z .

3. The Numerical Scheme

3.1.) *Scaling*

An important step in order to determine the relevant control parameters for this problem, and therefore the extension of the parameter space to be explored, is to non-dimensionalize the system of equations. In this case, we have chosen to measure all lengths in units of the jet radius a , and time in units of the sound crossing time $t_{\text{cr}} = a/v_{\text{sound}}$ (v_{sound} is the initial isothermal sound speed on the jet’s axis: $r = 0$, $t = 0$). Also density and pressure are expressed in units of their values at $r = 0$ and $t = 0$ while the velocities are expressed in terms of v_{sound} . With this choice of non-dimensionality, the control parameters are then reduced to the jet (internal) Mach number

$$M = \frac{v_z(r=0, t=0)}{\sqrt{\Gamma} v_{\text{sound}}} ,$$

and the density ratio ν .

3.2.) *Integration domain and boundary conditions*

Integration is performed in cylindrical geometry and the domain of integration ($0 \leq z \leq D$, $0 \leq r \leq R$) is covered by a grid of 750×250 grid points. The axis of the beam is taken coincident with the bottom boundary of the domain ($r = 0$), where symmetric (for p , ρ and v_z) or antisymmetric (for v_r) boundary conditions are assumed. At the top boundary ($r = R$) and right boundary ($z = D$) we choose

free outflow conditions, imposing for every variable Q null gradient ($dQ/d(r, z) = 0$). These free conditions do not completely avoid back-reflection phenomena from the outer boundaries. In order to limit this effect, the boundaries should be placed as far as possible from the region of the jet where the most interesting evolutionary effects presumably take place; for this purpose we employ a nonuniform grid both in the longitudinal (z) and the radial (r) directions (Fig. 1). In the radial direction the grid is uniform over the first 50 points and then the mesh size is increased assuming $\Delta r_{j+1} = 1.015\Delta r_j$. In this way the jet spans over 20 uniform meshes, while the external boundary is shifted to about $r \simeq 66$. as for the z -direction, we assume constant grid in the central part of the domain, i.e. in a sub-domain of length 40, between 150 and 600 grid points; conversely, in the remaining part we consider an expanded grid increasing the mesh distance according to the scaling law $\Delta z_{j\pm 1} = 1.015\Delta z_j$, where the minus sign applies in the first 150 grid points and the plus sign above 600 grid points. This non-uniform grid has high resolution in the region where the jet's head is maintained by the co-moving reference frame; at the same time it has the advantages to place the boundaries as far as possible and to allow to study the backflow and the cocoon structure for a longer time, before boundary reflection effects set in. As a comparison, Loken et al. (1992) adopted a 1200×350 non uniform grid in the radial direction, while Blondin & Cioffi (1992) used a 600×300 uniform grid. The design of our grid allows us to achieve a better resolution in the central region of the domain and a coarser grid in the peripheral parts with respect to Loken et al. (1992); however, with our approach, we manage to keep most of the cocoon in this central region. Conversely, Blondin & Cioffi (1992) obtain a higher resolution but with a smaller size of the domain.

The numerical scheme adopted is of PPM (Piecewise Parabolic Method) type and is particularly well suited for studying highly supersonic flows with strong shocks (Woodward & Colella 1984, see also Bodo et al. 1994, 1995).

4. Dynamical evolution

4.1.) General features

The general features of the evolution of a jet's head propagating into an external medium have been widely described in the literature since the presentation of the first simulations by Norman *et al.* (1982, 1984) and, in order to put our results in the full context, we summarize them here briefly. The early phases are essentially related to the unfolding of the initial discontinuity between jet and external material into i) a reverse shock propagating in the jet against the flow, ii) a contact discontinuity, separating the jet material from the external medium, and iii) a shock propagating in the external material. We can therefore distinguish five different regions in the evolved structure: 1) the jet proper; 2) the shocked jet material still flowing in the forward direction; 3) the shocked jet material reflected backwards at

the contact discontinuity and flowing back at the jet side; 4) the shocked external material; 5) the unshocked external material. The shocked jet and external material forms an expanding overpressured region which is called cocoon. The high pressure cocoon squeezes the jet and drives into it shock waves, which reflecting on the axis assume the characteristic biconical shape seen in the simulation results. These shocks modify the structure of the jet head and affect its propagation into the ambient medium. This complex interaction is the object of our investigation and will be discussed in detail in the following sections. The results of the interaction depends on the parameter M and ν , which define the jet, and therefore the morphology of the cocoon will be determined by the choice of these parameters.

The strength of the shock waves, driven by the cocoon into the jet, and the jet squeezing depend on how much the cocoon is overpressured. The cocoon pressure is in turn determined by the kinetic energy flow, thermalized at the jet shock, and by the cocoon expansion. We therefore expect a higher pressure for jet of higher Mach number and lower density: in this case, in fact, the energy flow into the cocoon is higher. This is confirmed by our numerical results that show a stronger dependence on the Mach number and a weaker dependence on the density ratio, in agreement with the simplified analytical model by Begelman & Cioffi (1989). A stronger interaction between biconical shocks and jet head is therefore expected for high Mach number jets and it is in fact in this parameter range that our results show different behaviours related to this interaction. The jet thrust can be modulated by the biconical shocks impinging on its head and this can produce a periodic increase in the advance velocity of the head, leading to a strong change in the cocoon morphology. In order to study in detail these processes, we have carried out several simulation runs exploring the parameter plane (ν, M) for underdense, hypersonic jets. Fig. 2 shows the effective extent to which we have explored the (ν, M) -parameter space. Different symbols (bullets and circles) refer to the different behaviors mentioned above and discussed in more detail below. In subsection 4.2 we will examine in detail how the advance velocity is modified by the jet perturbations, while in subsection 4.3 we will examine the effects on the cocoon morphology.

4.2.) *Velocity of the jet's head*

The advance velocity of the jet's head can be estimated on a first approximation by balancing the ram-pressure exerted by the jet front, $\rho_j(v_j - V_h)^2$, with the analogous force exerted by the external medium $\rho_{\text{ext}}V_h^2$ (see e.g. Norman et al. 1982, 1984). The equilibrium condition between these two forces gives the head velocity as

$$V_h \simeq \frac{v_j}{1 + \sqrt{\nu}} , \quad (1)$$

Since this value will serve in the following for comparison, it will be indicated by V_h , while the actual head velocity obtained from the numerical results will be indicated by v_h . The numerical results obtained by many authors give in general a velocity lower than V_h . Lind et al. (1989) give an interpretation for this lower velocity, noting

that the areas on which the two ram pressures exerts can be in general different and this amounts to changing Eq. 1 as follows:

$$V_h \simeq \frac{v_j}{1 + \sqrt{\nu/\epsilon}},$$

where $\epsilon = A_j/A_h$ takes into account the expansion (or contraction) of the jet at the head. Since, in general, the jet head tends to expand, its advance velocity will be correspondingly lower than that estimated by Eq. 1.

However, as discussed above, the interaction of the biconical shocks with the jet head can lead in some cases to a contraction of the head area and correspondingly to an advance velocity larger than that predicted by Eq. 1. In order to discriminate between these two behaviours, we have plotted in Fig. 3, the distance z_h , covered by the jet's head, as a function of the normalized time τ defined below, for jets with different values of the parameters M and ν .

A typical difficulty one has to face in comparing results obtained with different parameters ν and M is that the evolution proceeds at a different pace for every set of parameters, i.e. comparable configurations can occur at different epochs. Following Cioffi & Blondin (1992), we treat this problem introducing a ‘normalization’ time, t_{norm} , defined as the time employed to cover the unit distance (i.e. the jet radius) moving at the velocity V_h (Eq. 1). Configurations at the same $\tau = t/t_{\text{norm}}$ are, within reasonable approximation, in a similar evolutionary stage and can then be compared. We will therefore make use of this normalized time τ in every plot representing the temporal evolution of some quantity. In our units defined in Section 3.1, we have $t_{\text{norm}}^{-1} = M/(1 + \sqrt{\nu})$ and $\tau = tM/(1 + \sqrt{\nu})$.

The use of the normalized time τ in Fig. 3 makes very easy to distinguish between jet's head propagating at velocities above or below the value given by Eq. 1. In fact, this value corresponds to the line $z_h = \tau$. In the figure we have a group of curves lying above this line, indicating larger velocities and a group of curves lying below, indicating lower velocities. The higher velocities are found for high Mach number jets with low values of ν , while in all the other cases the velocities are lower and tend to decrease with time as already discussed by various authors.

We can gain a better understanding of the differences between the two classes looking at the behavior of the head velocity v_h as a function of time. The three panels in Fig. 4 show the results obtained for the cases $M = 100, \nu = 10$; $M = 3, \nu = 10$ and $M = 100, \nu = 100$. The first case belongs to the high (head) velocity class, while the other two cases belong to the low velocity class. We can immediately notice a great difference in behaviour between the first case and the other two: in panel a) we see that the velocity oscillates almost periodically, staying always above the value V_h showed for comparison as a dashed line; in panels b) and c) the velocity decreases systematically showing irregular oscillations of low amplitude and is well below the value V_h for case b).

We can follow in more detail two events of increase of the head velocity through

a sequence of contour plots of the distribution of the intensity of the longitudinal momentum flux ρv_z^2 in the r, z plane (Fig. 5). The time of each frame of the sequence can be traced on the velocity plot (Fig. 4). Frames a) and b) show a strong (nonlinear) perturbation, excited by the backflow interacting with the jet's wall; it travels towards the jet axis, reaching it and causing a steepening of ram pressure at the axis that accelerates the head's advance. In fact the first maximum of Fig. 4a occurs after the time employed by the perturbation to cover one jet radius. As time elapses, this perturbation is reflected at the axis, reaches the edge of the jet (frames c, d) and is reflected back again towards the axis and reaches it in the head's region (frames e, f), with the consequent increase of v_h that leads to the second maximum, that in fact corresponds to the time employed by the perturbation to cover twice the jet radius. The same reasoning applies for the following maxima.

Fig. 6 represents a sequence of contour plots of the distribution of the intensity of the longitudinal momentum flux, as in Fig. 5 above, but for a low Mach number jet, e.g. $M = 3$ and $\nu = 10$. We can clearly see the formation of the biconical shocks and their interaction with the jet head. The relevant difference is that the strength of the ram pressure perturbations results much lower than in the previous case. This can be more clearly seen looking at the plots of the same quantity as a function of the longitudinal coordinate z , on the jet axis, presented in Fig. 8: the periodic increases in momentum flux are present also in this case (panel b) but they have a much lower amplitude. As discussed in Section 4.1, in the low Mach number regime we expect a much lower cocoon pressure and therefore a much weaker perturbation induced in the jet by the cocoon. Fig. 9 shows the temporal behaviour of the average cocoon pressure and we can note the low values for this case (panel b) compared with the other two high Mach number cases. Following the evolution of the jet's head in the sequence of images in Fig. 6, we notice that it tends to expand further weakening the effect of the biconical shocks, with a consequent slower progress in the ambient medium.

The two classes discussed above are shown with different symbols in the Fig. 2 representing the explored parameter plane. Bullets (region 1) indicate those cases for which the head velocity v_h presents large quasi periodic oscillations and is in the average larger than V_h ; empty circles (region 2), instead, indicate the cases in which $v_h < V_h$, with irregular low amplitude oscillations. In this distribution we can note that the high velocity class is bounded at low Mach numbers and at very low jet densities compared to the external medium (high ν). The same process of generation of biconical shocks, which in turn interact with the jet head is at work also in the low velocity region 2 of the parameter plane but it is not able to impart sufficient momentum to the head and increase in a sensible manner its velocity. The reasons why this does not happen are however different for the low Mach number jets and for the low density jets.

We investigate at this point why the low density cases ($\nu > 30$) present characteristics similar to a low velocity behavior. Looking at Figs. 7c and 8c for the case $M = 100$,

$\nu = 100$, in fact, we see large values of the cocoon pressure and consequently of the momentum flux perturbations, but, on the contrary, the head velocity does not show corresponding large variations. The answer can be found looking again at the sequence of images of the momentum flux distributions for this case, presented in Fig. 7. Comparing these images with the corresponding images for the case $M = 100$, $\nu = 10$ (Fig. 5), we see that in the lower density case the biconical shocks form a larger angle with the jet axis: the jet compression is therefore immediately followed by a strong expansion and the increased thrust acts on the head for a very short time only. The momentum imparted to the jet's head is therefore low and the same is true for the increase in velocity. In the higher density case, on the contrary, the biconical shocks forms a small angle with the jet axis, the enhanced thrust acting on the head can last longer and the resulting increase in velocity is greater. The critical parameter appears therefore to be the inclination of the biconical shocks and this in turn appears to depend mainly on the density ratio ν : for low values of ν we find small angles between the shocks and the jet axis and the angle increases increasing ν . This explains why we find the borderline for the high velocity behaviour at $\nu \simeq 30$ (Fig. 2).

4.3.) Cocoon morphology

As discussed before, the particular setup chosen allows to study how the morphology of the cocoon varies in different regions of the parameter plane, and to compare then with the observed morphologies of radio sources. Figs. 10a,b represents two typical morphologies corresponding to the two regions of different behavior of the head velocity: the bimodal behaviour of v_h , discussed previously, reflects on this morphology. We measure the shape of the cocoon, given by the contour of the tracer $f > 0$, as shown in Fig. 11: here L is the longitudinal size of the cocoon, Y_M the maximum radius, and X_M the position of this maximum radius with respect to the jet's head. The ratios Y_M/L and X_M/L characterize the different morphologies.

In Fig. 12a) we show Y_M/L against τ ; from this figure we note that, as time elapses, the values attained by the ratio $Y_M/L \simeq 0.2 - 0.4$, with a tendency for high M to produce low values of Y_M/L . Begelman & Cioffi (1989) (see also Loken et al. 1992 for a more general formulation) have given estimates of the temporal evolution of the cocoon ratio Y_M/L , under the assumption of constant $v_h \ll v_j$ for a cylindrical cocoon. They find that the ratio varies with time as $\propto t^{-1/2}$; in Fig. 12a) stars show this analytical result as a reference. More interesting is the temporal behaviour of the ratio X_M/L for the different parameters (Fig. 12b). Here the bimodal structure is again apparent: jets in region 1 of the parameter plane produce cocoon with elongated morphologies ($X_M/L \simeq 0.6$) as in Fig. 10b) ('spearhead' cocoon), while jets in region 2 lead to cocoon morphologies that present the largest radius towards the head ($X_M/L \simeq 0.2$) as in the example of Fig. 10a) ('fat' cocoon).

This different behaviour can be interpreted examining the variation of the shape of the cocoon during the episodes of sudden acceleration of the jets in region 1. Two

of these episodes are represented in the two panels of Fig. 13, and we see that, for each velocity increase, the jet’s head surpasses the position of the old bow shock creating a new smaller bow shock yielding a global V shape. For jets in region 2, instead, this does not happen and the cocoon tends to expand at its front, giving a completely different morphology.

Comparing the obtained morphologies to the simulation by Loken et al. (1992), we note a qualitative difference in the shape of the cocoon. We recall that we consider an initial pressure balance between the jet and the ambient, while Loken et al. (1992) study an overpressured jet. However, we think that the main reason lies in the different initial setups chosen: in our case it is possible to follow the fate of the backflow due to the head interaction, i.e. the cocoon is fully contained in the domain, while in the case of Loken et al. (1992), and also Blondin & Cioffi (1992), the backflow is partially lost through the left boundary since the very beginning.

We finally add a comment about the limits of a 2-D geometry. We know that in 2-D large scale structures tend to be favoured, therefore some of the features one finds in 2-D simulations could not form, or be unstable, in a complete 3-D treatment. However the qualitative behaviour of the interaction can be captured in a simplified 2-D geometry. In fact, 3-D simulations by Hardee & Clarke (1992) and Hardee, Clarke & Howell (1995) show that key features, such as biconical shocks, are present also in a fully 3-D geometry.

5. Astrophysical applications and conclusions

We have discussed the physical characteristics of the interaction of supersonic, underdense, cylindrical fluid jets with a homogeneous, undisturbed medium. In order to examine the different cocoon morphologies, as they evolve in time, we have employed a particular setup that allows to follow this evolution on long time scales. The application of the results obtained to extragalactic jets can be performed relating the morphologies emerging from the numerical calculations to those observed mainly in the radio band. A basic question that arises at this point is the following: which physical quantity is most suitable to represent the observed radio brightness distribution? Authors have usually considered the particle density as a tracer of the brightness distribution, especially as far as radio lobes were concerned, drawing conclusions on the bases of how this quantity ‘looked like’ in a given numerical experiment and comparing this to the astrophysical situation. Instead, the brightness distribution is a function of the relativistic particle density distribution in space and energy and on the magnetic field. In the present calculations we do not study these quantities leaving this aspect for a forthcoming Paper II. However we can already attempt to identify some quite general trend looking at the behaviour of the tracer f , that we recall provides snapshots of the spatial distribution of the jet particles.

Looking at the tracer distributions in simulation runs with different values of M

and ν , we have noted a typical bimodal behaviour that we have interpreted on the basis of the temporal, and spatial, evolution of the longitudinal momentum flux ρv_z^2 . Thus, from the point of view of the cocoon morphology, slow jets and fast jets with high density ratios behave differently from fast jets with low density ratios, as it is clearly apparent on Fig. 11b). Can this fact be, at least in a very broad sense, related to different radio lobe morphologies? In other words, is the cocoon representative of radio lobes?

To attempt answering this question, we compare the density distribution in Figs. 10a,b) to the tracer distribution as given in Figs. 14a,b), for the same values of M and ν . We recall that f suffers from numerical diffusion in its evolution and, albeit being initially 1 inside and 0 outside the jet, it assumes values intermediate between these two extremes as turbulent effects develop. However, as discussed in Bodo et al. (1995), f remains a good marker of the jet particles. Going back to Figs. 10 and 14, we note that, for $M = 100$, the shock that surrounds the cocoon involves matter of the external ambient. Is this shocked region site of particle acceleration? If the answer is positive we can say that the form of the lobe resembles the density distribution of Fig. 10b), with an elongated structure having the front part protruding from the lobe. Similar morphologies can be found in the sample of high luminosity radio sources by Leahy & Perley (1991); representative examples can be: 3C42 ($(X_M/L)_{\text{obs}} \sim 0.75$), 3C184.1 (~ 0.8), 3C223 (~ 0.7), 3C441 (~ 0.7), 3C349 (~ 0.77), 3C390.3 (~ 0.6). In this scheme, the jet would be characterized by a high value of the Mach number accompanied by a moderate value of the density ratio. Moreover, the shock that surrounds the cocoon, according to simulations, must have the effect of enhancing the component of the magnetic field along the shock front, resulting in a high polarization at the source edge, with the polarization vector directed normally to the edge itself. This effect is clearly visible in the polarization maps of the sources mentioned above. In case of absence of particle acceleration in the external shock, and always assuming that the relativistic particles are carried along the jet following the tracer f , the ‘lobe’ would look like Fig. 14b), i.e. rather unusual to observations.

In the case of slow jet, we note from Fig. 10a) that the shock forms only in the front part of the cocoon, therefore the actual lobe has to have a morphology similar to that given by the tracer in Fig. 14a). Examples of this second kind of morphology can be found in the sample of Leahy & Perley (1991): 3C296 ($(X_M/L)_{\text{obs}} \sim 0.34$), 3C296 (~ 0.33) and 3C173.1 (~ 0.32) are good examples of this class, while 3C382 (~ 0.4) and 3C457 (~ 0.25) are less so; the remaining sources of the sample are more irregular and many appear to bear some characteristics of both kind. We note however that a detailed comparison must allow for possible projection effects: $(Y_M/X_M)_{\text{model}} \ll (Y_M/X_M)_{\text{obs}}$.

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Figure captions

Figure 1. Computational domain defined by $0 < z < D$ and $0 < r < R$, where $D = 139$ and $R = 66$. In the left panel, we show in black the initial jet area (defined by $0 < z < L$ and $0 < r < a$), symmetric with respect to the $r = 0$ axis. The right panel displays the non-uniform computational grid at scale 1 : 25.

Figure 2. Coverage of the parameter space: symbols indicate the cases in the (ν, M) -plane which we have actually computed. The different choice of symbols (bullets and circles) indicates regions with different behavior in the jet head advance velocity and in the cocoon morphology.

Figure 3. Plot of distance covered by the jet’s head z_h as a function of the normalized time τ . The values of the parameters are reported in the legenda.

Figure 4. Plot of head’s velocity v_h vs τ for $M = 100$ and $\nu = 10$ (solid line), the dashed line gives V_h as a comparison (panel a); The same as panel a but for $M = 3$ and $\nu = 10$ (panel b); The same as panel a but for $M = 100$ and $\nu = 100$. (panel c).

Figure 5. Sequence of contour plots of the distribution of the intensity of the longitudinal momentum flux ρv_z^2 in the $r - z$ plane, for the case $M = 100$, $\nu = 10$. The time of each frame is marked on the velocity plot in Fig. 4a.

Figure 6. Sequence of contour plots of the distribution of the intensity of the longitudinal momentum flux ρv_z^2 in the $r - z$ plane, for the case $M = 3$, $\nu = 10$. The time of each frame is marked on the velocity plot in Fig. 4b.

Figure 7. Sequence of contour plots of the distribution of the intensity of the longitudinal momentum flux ρv_z^2 in the $r - z$ plane, for the case $M = 100$, $\nu = 100$. The time of each frame is marked on the velocity plot in Fig. 4b.

Figure 8. Plot of the on axis longitudinal momentum flux profile ρv_z^2 , scaled with respect to the on axis initial value, for $M = 100$ and $\nu = 10$ (panels a, b) and for $M = 3$ and $\nu = 10$ (panels c, d), at the time corresponding to the first and second maxima of v_h for $M = 100$.

Figure 9. Plot of the temporal behavior of the average cocoon pressure vs τ for $M = 100$ and $\nu = 10$ (panel a); The same as panel a but for $M = 3$ and $\nu = 10$ (panel b); The same as panel a but for $M = 100$ and $\nu = 100$ (panel c). Dashed lines represent the power-law best fit $P_c \propto \tau^{-\eta}$ to the average cocoon pressure, to be compared to the analytical estimate $\eta = 1$ by Begelman & Cioffi (1989).

Figure 10. Gray scale image of the density for $M = 10$ and $\nu = 100$ (panel a, ‘fat’

cocoon), and $M = 100$ and $\nu = 10$ (panel b, ‘spearhead’ cocoon). This is an example of the two characteristic structures assumed by the cocoon.

Figure 11. Measuring a cocoon.

Figure 12. Temporal evolution of Y_M/L (panel a) and of X_M/L (panel b). The different sets of parameters are reported in legenda.

Figure 13. Gray scale images of pressure distribution for the case $M = 100$, $\nu = 10$ at two different times showing the effects of the head velocity variations on the cocoon morphology.

Figure 14. The same as in Fig. 10, but with the tracer.